Computational Fluid Dynamics modelling of sedimentation on Mars

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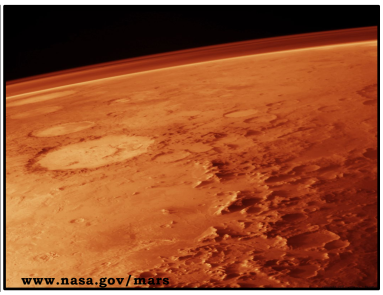
Why do *geo*morphologists study Mars?

- 3.5 billion years ago Mars was wet(ter) and warm(er), despite receiving 30% less solar radiation than today
- Planets like Earth and Venus have a surface tectonically active while Mars appears as having a solid mantle without any tectonic activity on surface
- Mars is now in the Amazonian period, started 3 billion years ago and characterized by craters and poor fluvial activity
- Challenge for Geomorphologist: 1) explain how Martian surface has conserved a much older sedimentary record than Earth; 2) the interaction of a planet with a changing and fainter young sun still preserved in sediments and landforms; 3) interpreting the currently forming features correctly
- An important issue: if life has formed, conditions under which it has formed can be constrained better than on Earth

Mars is the perfect testbed for models on Earth



Formation of sedimentary archives: gravity (potentially) matters

- Search for life for life on Mars means looking for traces of past life
- One place to find such biosignatures are deposits formed in water, both as habitat as well as archive
- To decide where to drill we need to understand how the rocks formed, and here the difference in gravity between Earth and Mars plays a critical role[1]

Flow hydraulics on Earth and Mars

The same amount of water, in the same channel, would flow more slowly, therefore at greater depth, but also less turbulent on Mars than on Earth. This will cause several effects on sediment sorting:

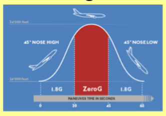
- Slower movement: less sorting
- Deeper runoff: longer settling distance for sediment to separate
- Less turbulence: less upwelling of fines, but relatively stronger lift and shear forces on bedload

Quantitative solutions to these questions suffer from the more unknown than known values for the variables used in empirical model

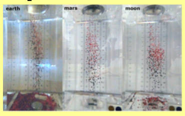
Scope for experiments to identify the scale of the problem, but need for computational fluid dynamics modelling.

Mars Sedimentation Experiments: MarsSedEx I to IV [3]

Parabolic flights offer zero or reduced gravity for up to 25 seconds



Particle	Diameter	Density	Gravity
Reference	1.05 mm	2.37	2.6
Basalt sphere	1 mm	2.75	2.9
Basalt sphere	0.7 mm	2.75	2.5
Basalt sphere	0.5 mm	2.75	2.7
Quartz sand	1 mm	2.77	2.9
Basalt sand	1 mm	2.77	3.0
Basalt sand	0.7 mm	2.77	2.8
Basalt sand	0.5 mm	2.67	2.3



Use of computer programs to predict settling sediment velocities

$m\frac{dv}{dt} = F_g - F_b - F_D = \Delta F - F_D$, where:

- $F_g = mg \rightarrow gravitational\ force,\ \ F_b = m\frac{\rho_f}{\rho_p} g \rightarrow buoynacy\ force$
- $F_D \rightarrow resistive\ force$

Defining $v = w = \frac{RgD^2}{vC_1 + \sqrt{0.75C_2RgD^3}}$, Ferguson and Church (2004)[2]

$$m\frac{dw}{dt} = \Delta F - \gamma w^2$$

$x(t) = w\left[\frac{2\cdot\ln(|e^{\beta t}+1|)}{\beta} - t\right]$, where $\beta = \frac{2w\gamma}{m}$ and $\gamma = \sqrt{\frac{\Delta F}{w}}$

Finite divided difference

$x(t)$ can be expanded in a Taylor series:

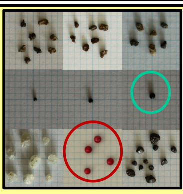
$$x(t_{i+1}) = x(t_i) + x'(t_i)(t_{i+1} - t_i) + \frac{x''(t_i)}{2!}(t_{i+1} - t_i)^2 + \ldots + R_n$$

$v(t) = x'(t_i) = \frac{x(t_{i+1}) - x(t_i)}{t_{i+1} - t_i} - \frac{R_1}{t_{i+1} - t_i}$. Defining: $t_{i-1} - t_{i+1} = h$:

$$v(t) = x'(t_i) = \frac{x(t_{i-1}) - x(t_{i+1})}{2h} - O(h)^2$$

From collected data x and t we are able to reproduce the temporal evolution of particles settling in water at different gravity conditions

Tests on two sets of solid spherical particles:



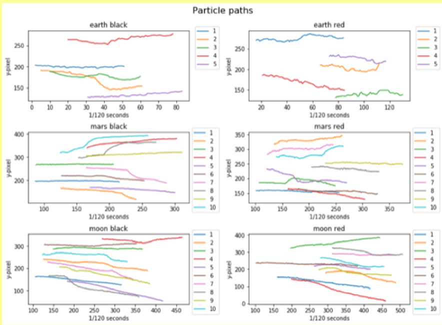
Black basalt particles, $D = 1.60\ mm,\ \rho = 2.65\ g/cm^3$

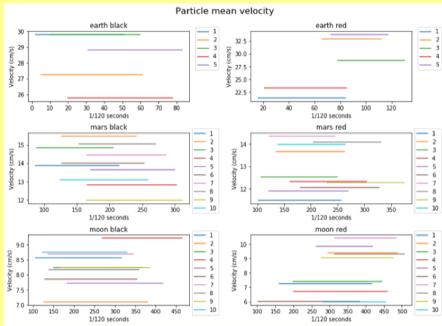
Red glass particles, $D = 1.02\ mm,\ \rho = 2.33\ g/cm^3$

For each set:

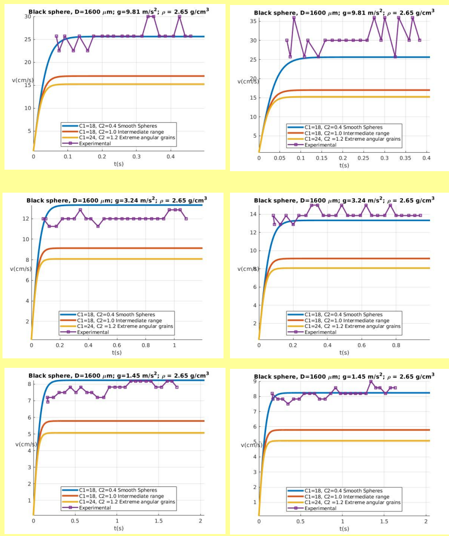
- **Settling in water at Earth gravity conditions (5-particle ensemble analysis)**
- **Settling in water at Mars gravity conditions (10-particle ensemble analysis)**
- **Settling in water at Moon gravity conditions (10-particle ensemble analysis)**

Particles path and mean velocity



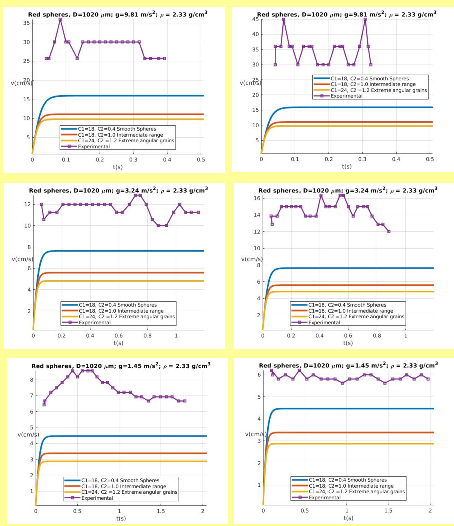


Black spheres settling on Earth, Mars and Moon



- **According to particle path, terminal velocity can be close to the theoretical value or largely <u>underestimated</u> (particles 4 on the left, 1 on the right);**
- **Relative error range from 6% up to 16%**
- **Particles close to wall container (externals) are less influenced from the others, providing the best agreement**
- **Evidence interplay between interactions with particles and reduced gravity (particle 9 on the left, particle 1 on the right)**
- **terminal velocity of external particles can be either <u>overestimated</u> and <u>underestimated</u> , with a relative error ranging from 8% up to 20%**
- **External particles interact with the wall container, exhibiting a terminal velocity apparently <u>overestimated</u> (particle 5, on the left)**
- **Internal particles are constrained on a more straight trajectory (particle 3 on the right)**
- **Relative error is of the order of 9%**

Red spheres settling on Earth, Mars and Moon



- **Red particles are slightly smaller than black ones; their paths are more influenced by the presence of the others;**
- **Mean settling velocity both for external (particle 3 on the left) and internal particles (particle 2 on the right) is <u>heavily underestimated</u>, with a relative error larger than 50%**
- **Settling velocity is largely <u>underestimated</u> for both external (particle 1 on the right) and internal (particle 8 on the right) particles**
- **The distribution is somehow bimodal, with half of the particle with a mean velocity comprised between 11 and 13 cm/s, and a second half between 13.5 and 14.5 cm/s, and relative error can be up to 50%**
- **External particles undergo important fluctuations (particle 3 on the left), while internal particles are constrained by the others to follow a straighter path (particle 6 on the right);**
- **Mean settling velocity is <u>underestimated</u>, with a relative error bigger than 50%**

Conclusions

- **Experiments in reduced gravity combined with computer analysis of trajectories of settling particles highlight severe limitations of semi empirical model to predict sediment settling velocity**
- **Further computational fluid dynamics analysis of sediment settling at reduced gravity conditions is needed to better understand the interaction mechanism between solid particles and solid and fluid phase.**

References:

[1] Grotzinger et al. in *Comparative Climatology of Terrestrial Planets*, 2013, p. 454
[2] R. I. Ferguson and M. Church, *A simple universal formula for grain settling velocity*, 2004
[3] N. J Kuhn, *Experiments in reduced gravity*, 2012